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MOBILE LUNAR MINER FOR OXYGEN

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ABSTRACT

A general design for a mobile lunar oxygen strip miner is given. The miner is designed to produce approximately 1 million kilograms of oxygen per year. The major components of the miner are discussed. Descriptions of the rotary auger, beneficiation conveyor, and overall system are given. A detailed description of the fluorine exchange oxygen extraction process is also given. A general cost analysis is included along with recommendations for further research.

INTRODUCTION

The need for oxygen in space propels us towards mining the lunar surface. The aim of this project is to produce 1000 tons of oxygen per year from the lunar soil. The mobile miner it is hoped will produce oxygen more efficiently than a permanent lunar facility. The efficiency being derived from the energy saved in transporting raw lunar materials to a permanent factory and by the lower shipping weight of a mobile miner.

The three main components of the strip mining operation are, a rotary auger, a benification conveyor belt, and oxygen extraction processing. A rear mounted rotary auger scrapes up the lunar soil and casts it onto the benification conveyor. The auger also propels the miner forward thereby conserving energy. A heated cathode will apply a negative charge to the soil particles as they are cast from the auger to the conveyor. It is assumed that the electrostatic properties of the soil will allow only small sized particles (< 800 micrometers) to stick to the belt. The belt will transport the fine particles to a supply hopper which will feed the oxygen extraction process.

The processing of oxygen from the concentrated lunar soil will take the following steps.

1. Fluorine will react with the oxides of Si, Ti, Fe, Al and Ca to liberate oxygen and potassium fluoride.

2. Oxygen is removed and purified by removing silicon tetrachlorides titanium tetrafluoride and unused flourine by hardened copper condenser and potassium iodide purifier column.

3. The potassium fluoride (KF) is sent through an electrolysis unit to separate fluorine and potassium for re-use in the initial reaction.

4. The oxygen is then cooled and stored as a liquid in a spherical tank.

We anticipate a very high level of automatic and remote control for the lunar miner operations with essentially no manned involvement on the Moon but with remote control by terrestrial operators. It is reasonable to assume that maintenance of the miner can be provided by one person.

GENERAL DESCRIPTION

The mobile lunar miner for oxygen is designed to be a miner and oxygen extractor in one machine. Lunar fines are scraped off the lunar surface by a cylindrical auger and conveyed to a supply hopper. The supply hopper supplies lunar fines for the oxygen extraction process. Once processed, the oxygen is liquified and stored in a spherical tank. The lunar miner is operable only during daylight periods - 336 hour working periods. The annual work time is approximatly 4000 hours. This figuire accounts for mechanical down-time and for the lack of solar heat during sun rise and set. Maintenance should be performed during night time hours.

The mobile lunar oxygen miner consists of nine major assemblies. Below is a brief description of each. More detailed descriptions are discussed later in the report:

1. Wheels and chassis - The chassis should be light weight but strong enough to support at least 80,000 kg on the moon. The present design uses four wheels to prevcent excess sinkage the wheels must have a wide track.

2. Rotary Auger - A drum shaped auger designed to agitatate and eject soil toward the beneficiation conveyor. The auger is located at the rear of the

mobile lunar miner.

3. Beneficiation Conveyor - A belt which will convey lunar fines (<800 micrometers) from the auger to the supply hopper. The fines are electrostatically separated from the coarser material.

4. Supply Hopper - A storage unit for lunar fines which is continually fed by the beneficiation conveyor. The supply hopper stores lunar fines for the oxygen extraction process.

5. Oxygen Extraction Process - This unit will extract the oxygen from lunar fines by a batch process using a fluorine exchange reaction. The fines are stored in the supply hopper above the process. Each time the process completes a batch more fines are extracted from the supply hopper.

6. Power Supply - This unit will probably be a nuclear reactor capable of producing at least 4000 kw to supply power for the oxygen extraction process, vehicle propulsion, auger, and conveyor systems.

7. Oxygen Storage Tank - A spherical pressurized tank which stores the liquid oxygen.

8. Cooling Unit - Located at the front of the mobile lunar miner and it cools the storage tank containing the liquid oxygen.

9. Automatic and Remote Control Unit - Contains camera and communications equipment. The camera scans the lunar surface and relays the picture back to a

control center (on moon, in space, or on the earth). Operators in the control center plot a course and send the information back to the mobile lunar miner. The control unit then responds by adjusting the lunar miners direction. The control unit also monitors the supply hopper to control the digging rate such that the supply hopper will never contain too little or too many lunar fines.

ROTARY AUGER

The auger and beneficiation conveyor system is designed to separate the usable materials in the lunar soil from the unusable materials. The system utilizes an auger wheel to agitate the lunar soil and direct the soil toward the beneficiation conveyor. The usable soil is carried by the beneficiation conveyor to the oxygen extraction hopper.

The auger wheel is required to perform a number of operations to the lunar soil it encounters. The three main operations are listed below.

1. Agitate the soil sufficiently to ensure the usable materials come in contact with the beneficiation conveyor.
2. Discard unusable materials the conveyor will not pick up.
3. Deal with variations in the lunar soil.

In order to perform the above operations the auger wheel design is broken down into the following categories:

1. Geometric Design
2. Motion (translation and rotation)
3. Material
4. Drive system

Each of these areas of the design must take into account the perfomance requirements and the lunar enviroment under which the system will operate.

GEOMETRIC DESIGN OF AUGER

The geometric requirements of the auger wheel are controlled by the intake rate of beneficiated material by the oxygen extraction process and the characteristics of the lunar soil. In order to produce the required annual amount of liquid oxygen the auger wheel and belt system must process approximately 228 kilograms of lunar soil per hour. This figure is the basis for the sizing calculations located in appendix A. The type of obstructions the wheel will encounter during operation should also be considered in the final design of the wheel.

MOTION OF AUGER

To provide undisturbed terrain for travel and for slight aid in propulsion the auger wheel and conveyor system is located at the back of the mining unit. The system is connected to the unit via a four bar parallelogram linkage (figure #1 appendix B). This linkage will allow the system to move vertically while keeping the same angle of attack at various digging depths. This motion is controlled by hydraulic cylinders between the unit frame and the connecting linkage (figure #2 appendix B). The rotation of the auger wheel is based upon the lunar soil conditions and the desired velocity of material as it leaves the wheel. The material must leave the wheel with a velocity such that the usable material will adhere to the beneficiation belt but not bounce off. This velocity will depend upon the exact distance between the wheel and the belt, the current soil conditions and lunar gravity. The exact value will need to be determined by experimentation. For our calculations, a velocity of .75 m/s was assumed.(see appendix A under auger geometry calculations)

MATERIAL

The auger wheel materials and construction requirements are determined by the lunar enviroment and soil. The material must be able to operate in extremely high and extremely low temperatures and also stand up to the abrasion of the lunar soil, including impact with subsurface rocks. Since impact with rocks is inevitable, the wheel material must be such that these ecounters cause as little damage as possible allowing the unit to continue operation without repair. To meet these requirements the material.must be tough with both a high hardness and high strength. Diamonds will be best suited for the rib edges.

DRIVE OF AUGER AND CONVEYOR

The drive of auger wheel and the beneficiation conveyor is accomplished by electric motors similar to those used on the lunar rover. The wheel and conveyor will each have a separate motor mounted on the four bar linkage. This type of arrangement is chosen to make use of the predesigned motor suitable for the dusty enviroment and to allow the unit to continue in operation should one motor fail.

BENEFICIATION CONVEYOR

Studies done on lunar strip mining consider electrostatic beneficiation as a major goal in most any mining operation. Beneficiation is desirable before chemical processing, because it reduces the energy requirements and the size of the chemical process. These benefits are especially significant when one considers a mobile lunar strip mining unit where size and energy requirements are most important Fortunately, the moon appears to offer the ideal environment for electrostatic beneficiation of ores. Beneficiation is a low energy process since it requires differentiation of the components by only their electrostatic properties.

The moon is considered the ideal location for electrostatic beneficiation to occur, because of the pristine quality of its soil. Uncontaminated by effects of humidity, the soil has a preserved characteristic surface conductivity. This permits the differential separation of grains by electrical forces.[1] Properties enhancing beneficiation on the moon are:

1) Lunar soil is in a fine particulate form.
2) Scientists suspect very strong electrification properties with the lunar dust.

3) Absence of water makes the dry beneficiation process more attractive.

4) Vacuum conditions eliminate any air turbulence problems.

5) Electrostatic methods beneficiate both magnetic and non-magnetic ores. This eliminates the need of magnetic separators which are heavy and require more energy. [3]

The studies consulted indicate that electrostatic beneficiation should work especially well when mining for anorthite ($Ca\ Al_2\ Si_2\ O_8$) in the lunar highland regolith and also when mining for ilmenite ($Fe\ Ti\ O_3$). These minerals are of particular interest to us since they will be the main components used after our beneficiation process. Ilmenite is also considered ideal for producing titanium. Actual data on beneficiation of lunar soils is practically nonexistent. The theoretical data indicates that a benefication process producing anorthite and ilmenite will result in very workable fines. Before good results can be realistically expected, it will be necessary to investigate various electrostatic beneficiation processes on the Moon. Methods of beneficiation are abundant. The three methods investigated were:

1) Triboelectrification

2) Selective conductive induction charging.

3) Heated cathode charging and selective conductive induction charging

Each of these processes are recognized to have potential for future use on the Moon. When designing a beneficiation process, a notable point is that much testing needs to be done before a precise process is developed to beneficiate a particular ore. Soil analysis of various regions will also determine the requirements of the beneficiation process. Studies for permanently based mining plants allow a year before beneficiation begins to play a major role in processing oxygen and other materials. It is suggested that one unit be designed and operated on the moon for a year. The results from this unit would then be used in designing future more efficient machines.[3] In designing our mobile unit, we sought to simplify our beneficiation process to allow easier modification. These modifications would be based on results of actual beneficiation on the moon.

The design of our beneficiation process consists of a heated cathode and beneficiation conveyor. The heated cathode is located behind the auger and below the beneficiation conveyor. The beneficiation conveyor extends from the auger to the top of the supply hopper located at the top of the rear of the lunar miner. The lunar soil is ejected from the rotary auger towards the beneficiation conveyor so it will come into contact with the conveyor. As lunar soil is ejected from the rotary auger it is charged by the heated cathode. The charging is done so that the finer soil particles (lunar fines) will stick electrostatically to the underside of the beneficiation conveyor. The beneficiation conveyor will move with a speed of approximately 0.35 m/sec. (appendix A under conveyor speed calculations) The coarser (>800 micrometers) soil particles will not stick to the conveyor due to their lower surface area to volume ratio. The lunar fines are then carried by the conveyor up to the supply hopper. The fines are scraped off the conveyor into the supply hopper by a scraper. A beneficiation efficiency of around 50% is sought. This means that approximately one-half the mass mined is discarded. The remaining 50% is sent on to the process. The beneficiation process will yield the smaller particles, and will differentiate the ores by their electrostatic properties. The design of the conveyor belt and its material properties will also be based on tests of electrostatic properties on the moon.

SUPPLY HOPPER

A dust hopper will be used to assure an adequate supply of usable lunar material to the oxygen extraction process. As material is removed from the beneficiation conveyor it will fall into a hopper. This hopper will act as a supply bin for the oxygen extraction process. The size of this hopper must be large enough to insure that the reactors can be filled with lunar material on demand. However, it must not be oversized since this would extract weight in both equipment and stored soil. The interior of the hopper is sectioned off to provide separate bins for each reactor. Each of these bins can operate and drain separately to allow independent operation of each reactor.

OXYGEN EXTRACTION PROCESS

After the beneficiation process the concentrated lunar fines must undergo chemical processing in order to extract oxygen. There are a variety of procedures being investagated that will convert lunar soil into productive materials. The following is a list of processes used in producing oxygen:

1. Fluorine Exchange
2. Hydrogen Reduction
3. Hydrogen Sulfide Reduction
4. Carbothermic Reduction

Through researching these various procedures we have found that fluorine exchange proves to be the most efficient method. The use of fluorine is prefered because thermodynamically all metal oxides should react with fluorine to liberate oxygen; the reactions take place at temperatures lower than 500° C. The fluorine process enables us to take advantage of almost all components found in benificated lunar fines.

A major advantage of fluorine exchange is the efficiency of oxygen recovery. For each 100 lbs. of soil supplied to the processor 42 lbs. of oxygen will be generated, this figure can be compared to the 3.2 lbs. produced by hydrogen reduction [10]. Other advantages of using flourine would be the low operating temperatures, due to the reactions being exothermic very little energy is needed to conduct the process. The average temperature is 500' C in contrast to the 1500' C and 1600' C needed for hydrogen reduction and carbothermic reduction, respectively. This lower temperature will reduce the bulk weight of the process enough to cancel any loss acquired by the extra weight of the flourine and potassium.

The vessel needed for fluorine exchange will be cylindrical in nature, and have a volume of .25 cubic meters. The cylinders will have a weight of less then 90 Kg and be able to accomadate 205 Kg of lunar soil, having a density of 1600 Kg/M3. The process will be a batch mode operation, which will deposit soil in the top, and remove free metals from below. Because the reaction does not require the addition of thermal energy, the dust cloud generated during loading and unloading will not create any problems. The cylinders will be copper lined with a maximum temperature of 900' C. There is a 2 hour cycle time for this process. The tank is filled to 50% capacity to allow for gas build up. The process will consume 200 Kg of lunar soil to yield 87 Kg of oxygen.

The soil processed will consist of the following oxygen compounds.

Silica	43%
Iron Oxide	16%
Alumina	13%
Calcium Oxide	12%
Magnesia	8%
Titania	7%
Others	1%
	=====
	100%

These compounds will react with fluorine directly producing oxygen and metal fluorides by the following reactions. The consumption rate is 2.2 Kg of fluorine for each 1 Kg of oxygen produced.

$$SiO_2F_2 \longrightarrow SiF_4 + O_2$$

$$2SiO_2 + 2F_2 \longrightarrow 2SiOF_2 + O_2$$

$$TiO_2 + 2F_2 \longrightarrow TiF_4 + O_2$$

$$2TiO_2 + 2F_2 \longrightarrow 2TiOF_2 + O_2$$

$$2Al_2O_3 + 6F_2 \longrightarrow 4AlF_3 + 3O_2$$

$$2CaO + 2F_2 \longrightarrow 2CaF_2 + O_2$$

$$2MgO + 2F_2 \longrightarrow 2MgF_2 + O_2$$

$$2FeO + TiO_2 + 6F_2 \longrightarrow 2TiF_4 + 2FeF_2 + 3O_2$$

These reactions occur in the temperature range of 0' C to 800' C, and a pressure range of 13 KPa to 130.KPa. Although measurable yields will begin at 25' C and 53 KPa the optimal conditions are 500' C and 101.KPa. There is a linear increase in reaction rate as temperature increases. The maximum temperature will be around 900' C.

The products of these reactions are free metals and oxygen. The oxygen is mixed with silicon and titanium tetra-fluoride and unused fluorine. In order to seperate oxygen from fluorine there is a condensor in series with a potassium iodide column purifier to remove the tetrafluorides and remaining fluorine. The condensor should operate at -100' C and 101 KPa. The low temperatures can be achieved by shadow shading.

The oxygen is then pumped to a turbomachinery type compressor in order to become liquified. Liquification of oxygen takes .11 million calories for each kilogram reduced. To produce our 87.4 Kg/hr it will require 9.61 million calories, and consume approximately 380Kw. The compressor is approximately 2.65 m3 and the cold box is 1.4 m by 2.8 m. The liquid oxygen, having a density of 1140 g/m3, will be stored in a spherical container with a volume of 50 m3. The sphere will hold 57 Kg of liquid oxygen and have a weight of 115 Kg.

The metal fluorides will now undergo a second reaction with potassium in order to recycle fluorine.

The following is a list of the chemical reactions of potassium and the fluorides.

$SiF_4 + 4K \longrightarrow 2KF + Si$

$FeF_2 + 2K \longrightarrow 2KF + Fe$

$AlF_3 + 3K \longrightarrow 3KF + Al$

$CaF_2 + 2K \longrightarrow 2Kf + Ca$

$MgF_2 + 2K \longrightarrow 2KF + Mg$

$TiF_4 + 4K \longrightarrow 4KF + Ti$

Potassium vapor reacts with metal fluorides at a temperature of about 800' C and pressures of 13 KPa to 37 KPa. The liquid potassium fluoride will be produced from these reactions. The liquid potassium then undergoes electrolysis. The electrolysis process will be preformed at a temperature of 900' C and a pressure of 37 KPa to 107 KPa. The prefered, but not critical, conditions are 915' C and 101 KPa.

The electrolysis unit will be 5.7m3 and will weigh roughly 4500Kg. It will need 250 Kw of power and have a heat rejection of 44 KJ/s. The fluorine gas, which is recovered at the positive electrode, and the potassium gas recovered at the negative electrode, are then pumped back to their reservoirs for future use in the reactor.

AUTOMATION

The adverse and remote conditions under which the lunar miner will operate require the unit to be as independent as possible. To achieve maximum independence all systems will be automated. The extent of automation will be dictated by the characteristics of each system / its required functions and possible problems the system may encounter. The automation of the miner is broken down into the following systems:

1. Auger/Belt System
2. Vehicle Path and Drive Train Control
3. Oxygen Extraction Process
4. Storage and Cooling
5. Power Supply
6. Main Control Unit

Each automation system must be designed to operate and control its system at peak efficiency,interact with the other systems, adjust to changing enviromental conditions and effectively handle most problems that develop. The unit should only request auxillary assistance when the problem cannot be solved internally. The automation systems should, however, be in continual contact with a remote observation/monitoring station.

AUTOMATION of the AUGER and BENEFICIATION BELT

The auger and beneficiation belt require a system to monitor and adjust to the encountered soil conditions and the amount of usable material being delivered by the belt. This system will require two main data inputs. A torque sensor located on the auger wheel and a level indicator in the oxygen extraction hopper. By combining the data from these inputs the auger/belt system will be able to efficiently provide the oxygen extraction process adequate amounts of usable material.

The torque sensor on the auger wheel will provide information on current soil conditions. Soils of differnt consistencies and composition will require differing amounts of energy during agitation. If the soil is such that too much energy is requied to adequatly process it the unit will pickup the auger wheels and move to another location and continue. The torque sensor will also serve to protect the auger wheels when they come in contact with large rocks which could cause undue wear and energy expenditure. Instead of attempting to grind through the rocks, the unit can once again pick up the wheels and move past the obstruction.

A level indicator in the extraction hopper will provide data on the amount of usable material being accumulated by the auger/conveyor system. This data will be used with the torque sensor data to determine the relative efficiency of the beneficiation process. The system can vary the speed of the belt and auger wheel or move to another area if the system is not functioning within specified efficiency standards.

The level indicator in the oxygen extraction hopper also acts as a interface between the auger/beneficiation belt and actual extraction process. If the level in the hopper becomes low, the auger/belt system reacts by delivering usable material at a greater rate. If the level in the hopper becomes extremely low the extraction process can slowdown or shut off until the level increases. The level indicator also prevents the auger/belt system from becoming over productive by slowing it down when the hopper is near full. The total effect of this system is to provide usable lunar material to the oxygen extraction process as efficiently as possible.

VEHICLE PATH and DRIVE TRAIN CONTROL

With each wheel separately driven, the path of the vehicle can be controlled by varying the speed of each wheel or sets of wheels on either side. This system will require some outside assistance. Video cameras on the unit will send the image of the surrounding terrain to a remote monitor (lunar, orbital or on earth). A remote operator will observe the suurounding terrain, note obstacles and areas which appear best for oxygen extraction, and plot in a path for the vehicle. Due to the slow rate of the miner the path will only have to be set about every 24 hours.

AUTOMATION of OXYGEN EXTRACTION PROCESS

The automation system will monitor and control the oxygen extraction process. To accomplish this the system must have control of all valves, pumps and gates in the process and receive data on the level in the reactor and the flow of extracted oxygen. Data from level indicators in the fluorine reactor will be used to control the inlet valves of each substance. When proper levels are reached the valves will close. The amount of oxygen extracted in the reactor and pumped through the condensor is monitored by a flowmeter in the oxygen line. When the rate of oxygen flow falls below the specified amount, the reactor will shutdown. The substances will be removed and the process will start over.

STORAGE and COOLING of OXYGEN

The automation of the cooling and storage system requires two main data inputs, a level and a pressure indicator in the storage tank. In addition, the system requires control valves on the tank to control filling. With these inputs the system may control the filling and storage of the oxygen tanks and monitor them to ensure they are operating properly.

AUTOMATION of POWER SUPPLY

Requirements:

1. Monitor consumption
2. Monitor reserve power
3. Monitor and control power generation
4. Allert all applicable systems and remote station if shutdown or failure is eniment

The system to meet the above requirements will depend on the type of power supply(s) used.

MAIN CONTROL UNIT

A main control unit must be developed to control the various processes on the miner and handle communications. This control unit must take input data from various sources on the miner and react accordingly. A specialized computer controller integrated with a telecommunications device will operate the miner and send all data to the monitoring station. This unit should be able to function independently, however, remote override should be possible at all times.

POWER SUPPLY

Power generation can be performed by a variety of methods. Solar, nuclear, or a combination of the two may be feasible for the mobile lunar oxygen miner. Solar power alone would be difficult considering the high power demands of the fluorine exchange oxygen extraction process. Nuclear power or a combination of nuclear and solar power seem to be the most feasible for the lunar miner. However, at present we will assume that nuclear power will probably provide the majority of the energy required by the lunar miner. Solar power utilization is not discussed in this report. The majority of the power consumed by the mobile lunar miner will be for the fluorine exchange oxygen extraction. The power required for the lunar miner should be near 4000 kilowatts.(see section on oxygen extraction process)

A compact particle bed nuclear reactor has been described by J.R. Powell et. al. (1984). This reactor has a rod type geometric configuration for packed bed "elements" interspersed in a hydrogenous moderator matrix. An inert gas coolant flows radially inward through the reactor. Inlet coolant flows first by the moderator and then by the higher temperature packed bed "elements" before exiting. Coolant pressure should be between 5 and 10 megapascals. The reactor would operate at 1500' kelvin. The optimum number of fuel elements is between 9 and 19.

Three compact reactors capable of producing an average of 4000 kW of thermal power are discussed by J.R. Powell et. al., 1984). The smaller one is significantly lighter than the other two and is probably best suited for purposes of a lunar vehicle. This reactor can operate in a variable power mode producing an average thermal power at 4000 kW with peak power up to 20 megawatts. Refueling would be yearly. The overall diameter of the reactor would be about 1 meter and would weigh approximately 500 kilograms.

The reactor could be coupled with a Brayton cycle to convert approximately 25% of the thermal power to electrical power (J.R. Powell et. al., 1984). The electrical power could then be used to power the fluorine exchange oxygen extraction process, auger, beneficiation conveyor, and all other utilities on the lunar miner. A reliable lightweight turbine will have to be designed so that it can be coupled effeciently with the reactor.

WHEEL ASSEMBLY AND CHASSIS

A detailed description of the wheels and chassis of the mobile lunar miner is omitted in this report due to the lack of information, as of yet, on the total mass of the vehicle. Several points can be made. If the lunar miner is to store all of the oxygen produced, during it 336 hour work period, its total mass will exceed 76,000 kilograms at the end of the work period. This extreme weight may not allow the wire mesh wheel design that exists on the lunar roving vehicle. A new design may be required. In addition, since wheel sinkage is inversely proportional to wheel footprint area, a wide wheel must be designed. Also, more than four wheels for the lunar miner may be necessary. A formula for wheel sinkage is given below;

$$Z = (W/(A*K))**(1/N)$$

where:

W = wheel load (newtons)

A = wheel footprint area (meters squared)

K = Kc / b + Ko = soil consistency

Kc = cohesive modulus

Ko = frictional modulus

N = exponent of soil deformation

CONSTRAINTS

Terrain - Rocky and/or high relief areas must be avoided, because the processing is designed for lunar dust and a relatively smooth surface.

Temperature - Operation time constraints exist due to the extremely low temperatures on the dark side of the moon, mining operations are limited to the lunar day. Special materials will be required to withstand the extreme temperature variation.

Weight - Due to high transportation costs, the weight of the machinery and supplies must be kept to a minimum.

Energy Source - Maximum use of energy is desired to minimize costs. Due to the large amount of energy required (~4000 KW) solar power is not feasible with today's technology.

Autonomous Control - Due to the 336 hour working day, manned operation is not practical.

Oxygen Storage - Due to the temperature on the lunar surface, energy is constantly required to store oxygen as a liquid.

Service - To simplify service, it must be performed in a shirt sleeve environment. Modular design will also shorten service time.

Efficiency - 42% from fines minimize travel distance without hindering efficiency of process.

COST ANALYSIS

It has become apparent that space travel will be a common practice in the future. certain goods may be more easily produced in space where vacuum and weightless conditions are advantages to the production of those goods. In addition certain scientific experiments and measurement are more easily performed in space due to conditions in space. This future increased space industrialization will necessitate a large consumption of oxygen for rocket propellent fuel as travel between space stations becomes standard procedure. However, to mass produce this oxygen on earth and then have it orbitally lifted from earth will be a very expensive process. The expense is due to the fact that much energy is required to lift liquid oxygen out of the potential energy well created by the earths gravity field. Projected calculations for future costs of orbital lifeting from earth are in the proximity of 654$/KG. [3]

A less expensive alternative is to mass produce oxygen on the moon. It is estimated that orbital lift from the moon will require 1/7 the energy requirements as orbital lift from earth. however, in order for it to be economically desirable to produce oxygen on the moon, space travel must increase so that the initial high costs for producing oxygen on the moon will be surmounted by the long term savings. The initial high costs include the research, development, design, manufacturing, shipping, and start-up costs for the lunar oxygen production operation. Lunar oxygen production will continue to be expensive until the operation becomes self-sufficient, and oxygen from the moon is mass produced and mass consumed. [3]

How quickly the savings can be realized depends on two factors:

1. The amount of lunar oxygen consumed per time period after start-up.
2. The actual prestart-up and poststart-up costs of the operation.

The amount of oxygen consumed so that these costs can be quickly overtaken by long term savings is referred to as the break-even consumption point (see figure 5 and 6 appendix B). The lower the costs involved, the lower the break-even consumption point will be. Therefore it is extremely important that the lunar oxygen production process be designed so that it will be as efficient and cost effective as possible for both prestart-up and poststart-up time periods.

It has already been proposed in this report that the mobile lunar oxygen strip miner may be an efficient and less costly process for oxygen production. Advantages for the mobile lunar strip miner are outlined below.

1. <u>No lunar atmosphere</u>. Not only does the lack of an atmosphere on the moon decrease the energy requirements for lunar orbital lift, it is also advantageous in the oxygen extraction process for the lunar strip miner. Dust particles will be allowed to fall freely from wheel to belt with no air resistance. In addition, the lack of atmosphere preserves the electrostatic characteristics of the dust particles so that the beneficiation process will require less energy.

2. <u>One-sixth gravity</u>: The little gravity on the moon will allow transportation of the lunar soil through the process to be energy efficient. All of the mechanical devices such as beneficiation drums, belts, etc. can be made with very little mass since their weight on the moon and the weight of lunar soil will be minute.

3. <u>Abundant solar energy</u>: The energy radiating on the moons surface will not be filtered by an atmosphere and will be available throughout the full daylight period.

4. <u>Self-sufficient</u>: Since the mobile oxygen strip miner will contain the mining, beneficiation, oxygen extraction, and oxygen storage processes in one machine, it can be designed to produce oxygen for long periods of time without human interaction.

5. One machine to export from earth: Non-mobile oxygen mining processes will require exporting from earth many different machines (front-end loaders, haulers, and the oxygen extraction factory). The movile strip miner is compact and carries all processes in one machine.

6. Less energy wasted: Non-mobile oxygen mining processes require much kinetic energy spent by haulers making round trips to and from the oxygen extraction process. The mobile strip miner will be energy efficient in that transportation costs of the ore will be negligible. Although the oxygen extraction process will be hauled instead of the ore, the machines pace will be at a crawl (Appendix A under miner velocity calculations) so that spent kinetic energy will be minimal.

However, there are disadvantages inherent with operating on the moon that will be costly. They are as follows:

1. Hazardous environmental conditions for man.

2. A lack of atmospheric pressure will increase the costs of keeping fluids in containers.

3. Because of the nature of the lunar environment, all equipment will have to be specially designed.

4. Control of the mobile lunar strip miner will have to be completely automatic or a combination of automatic and remote.

5. Equipment will have to be designed so that maintenance time of the miner will be at a minimum.

Energy Costs For Extracting O2 From The Moon

Basically, the energy costs can be categorized into two areas. First energy costs for mining and second energy costs for lunar orbital lifting. The energy required for the O_2 mining process will be spent on vehicle propulsion, lunar soil digging, ore transportation, beneficiation, and fluorine exchange process. The fluorine oxygen extraction will require the majority of this energy. If the abundant solar energy can be harnessed, the energy costs for the mining operation can be at a minimum. By far, the energy costs for having the oxygen orbitally lifted will be the greatest. After the start-up of the operation the total costs should approach the oxygen ejection costs. Costs for oxygen ejection have been calculated to be 200$/kg at start-up to 65$/kg poststart-up.[3]

EQUIPMENT COSTS

Equipment costs should be small when compared to other costs. Projected calculations for equipment costs range from 25 to 600$/ton/year. These costs also include equipment associated with a maintenance facility on the moon. This facility will be a shirt-sleeve environment. Equipment costs for the oxygen extraction process are given in Appendix B, table 2.[3]

MANUFACTURING COSTS

Manufacturing costs include costs for building and installation of the mobile lunar strip miner and maintenance facility to be located on the moon. Design, shipping, and operational costs are not included. The manpower costs for installation will be high due to the hazardous environmental conditions. No figures for these costs have been estimated.

DESIGN COSTS

Design costs include all research and development costs for the design of the mobile lunar oxygen strip miner. Design costs will be the highest as compared with manufacturing and equipment costs. The environmental conditions which exist on the moon necessitate careful and extensive research and development. The lunar strip miner must run for extended maintenance free periods of time. This requirement dictates a modular design so that portions of the machine can be replaced quickly (i.e. wheel assemblies, transmission, etc.). The lack of pressure on the Moon requires careful design of fluid containers. Materials must be carefully selected due to the corrosive nature of the abundant solar energy and extreme temperature variations. All controls must be automatic and/or remote. The above requirements and others have given rise to a prediction of 1500$/lb for a non-mobile strip mining operation.[1] A mobile strip miner wil probably be more expensive to design.

SHIPPING COSTS

Shipping costs for a mobile strip mining operation should be less than that for a permanent site operation. The non-mobile operation requires more equipment than a mobile operation. The mobile operation can be started with one mobile strip miner and a maintenance facility. The shipping costs will involve orbitally lifting the equipment from earth and having it landed on the moon. Orbital lifting costs will average 654$/kg. [1]

TOTAL COSTS

The majority of the initial costs will involve the research and development costs (design costs), shipping costs, and installation. Figures for the design costs and shipping costs are 1500$/lb. and 654$/kg respectively. The annual costs should approach ejection costs after start-up. The ejection costs have been estimated to be 65$/kg for post start-up. [3]

HAZARD ANALYSIS

The environment in which the lunar miner will operate and the required production rate of oxygen produce several unavoidable hazards. The major hazards are listed below. The probability of each hazard occuring and the resulting damages must be taken into account when designing precautionary systems.

1. Improper Service and Maintenance

    Precaution; High level of training and education.

    Strict procedures and checklists required.

2. Equipment Malfunction

    Precaution; Design for high reliability.

    Back-up systems

    Proper shutdown procedure to prevent further damage.

3. Terrain Hazards

    Design to avoid or stand up to obstacles.

4. Unexpected Temperature Variation in Equipment

    Design for emergency shutdown and cooling

5. Dust

    Damage to equipment

    Poor visibility for video path control

Catastrophic Failures

1. Explosion of pressure vessels

   -destroy miner

   -injure near-by people

   -damage near equipment or facilities

2. Out of control drive system

   -Drive into natural lunar obstacle such as rock or crater

   -Damage to lunar equipment

3. Nuclear Reactor Malfunction

   -Destroy unit

   -Injure people

   -Damage or destroy lunar base

RECOMMENDATIONS

1. Maintenance Facility:

Research should be done on a maintenance facility to support the lunar miner. This facility should include a shirt sleeve environment where repairs and preventive maintenance can be performed. The facility should also include subfacilities to transfer and store liquid oxygen and to rejuvenate the miner's fluorine supply.

2. Rotary Auger Style:

Experiments must be done to determine the optimum style of the blade geometry for the rotary auger. The optimum style can be determined by measuring friction, digging speeds, auger wear, and power required for different prototype augers working lunar soil (or similar soil) in the laboratory. These experiments should be conducted for augers with different materials, size, weights, and blade geometries. Early experiments should be simple: i.e. auger lunar soil with a single blade to determine the optimum auger material. Later experiments should be conducted with a whole auger to determine the optimum auger width diameter, and digging depth for most efficient use of energy.

3. Beneficiation conveyor:

The beneficiation conveyor system is a very complicated system which will require much laboratory work to optimize. Several major areas of this system need to be investigated. Firstly and most important, is the ability of the heated cathode to charge soil particles in such a way that the fines of good quality stick to the conveyor. Due to electrostatic properties, the coarser non-usable particles fall off the benification conveyor. This electrostatic sorting ability is crucial to our design. Laboratory experiments in a vacuum will be required to optimize this process.

Another area to be investigated is the angle at which the conveyor belt should be mounted to the vehicle. The rotation speed of the conveyor should be optimized. If the conveyor moves too slow, there will be insufficient surface area for all usable lunar fines to stick. However if the conveyor moves to quickly energy will be wasted.(see Appendix A under beneficiation conveyor speed calculations)

4. Extracting Hydrogen From Lunar Fines

A combination oxygen and hydrogen extraction process would be more beneficial than the single oxygen extraction process since both elements are required for rocket fuel. If both these processes can be combined on the lunar miner, the extraction operation will be more valuable. Research should be done to develop a hydrogen extraction process which may be incorporated on the lunar miner.

5. Fluorine Exchange Reactor

Research needs to be done on the problem with the fluorine reactor experiencing corrosion attack on the reactor structures, or in general thermophysical deterioration which may be expected for all temperatures. The temperatures are hard to maintain since the reaction is exothermic. There is also a need to improve of the efficency and operation of oxygen purification.

6. Electrolysis Unit

A primary obstacle affecting the use of a potassium fluoride electrolysis system is the seperation of product gases from the incoming liquid. This can be achieved by using the form of electrolysis where gas is formed in the liquid, and externally seperated. Or there is the possibility of modifing the electrolysis unit to produce a gas with only evaporated and entrained liquids. The voltage requirements will be better controlled when the following constraints have better quality control.

1. Electrode catalytic activity or polarization losses
2. Lead losses in bringing current to the electrodes
3. Quantity of potassium fluoride in the cell
4. Internal resistance

7. Solar Energy Utilization

Research should be done in utilizing solar energy to provide power to the lunar miner. The lack of atmosphere on the moon and long daylight periods provide excellent conditions for harnessing solar energy.

8. Modular Design

The remote and harsh conditions of the lunar environment severely impair the ability of humans to do work on a machine that may be stranded on the lunar landscape. This condition makes it necessary that repair work be as fast and easy as possible. This requirement dictates a modular design. Repair work should be done by replacing whole assemblies instead of individual parts. Assembly mounting must be as simple as possible. Further research needs to be done in this area.

9. Wheel Assembly and Chassis

A detailed investigation of the lunar terrain and lunar soil mechanics should be conducted so that the type and size of wheels necessary to carry the mobile lunar miner can be determined. The mass of the lunar miner must be known at this point so that the wheels and chassis can be designed. A value of 85000 kg may be used as a rough figure.

10. Power Conversion

Detailed research needs to be conducted in adapting a compact nuclear reactor to the mobile lunar oxygen miner. This report has not covered the problem of converting nuclear power to electrical power. It has been suggested by J.R. Powell et. al. (1984) that a Brayton cycle could be utilized to convert at least 25% of thermal nuclear power generated by a compact particle bed reactor to electrical power. Lightweight turbine development efforts have been conducted by Westinghouse, Garrett, AI Research, and General Electric.

11. Liquid Oxygen Transportation

The problem of unnecessarily burning energy to transport large amounts of liquid oxygen across the lunar surface is of concern. The current design of the mobile lunar oxygen miner requires the vehicle to store all oxygen that is produced during one 336 hour work period. This amounts to 76,000 kilograms of oxygen at the end of the work period. This is an enormous amount which may be difficult and costly for the miner to transport across the lunar surface. An alternative is to reduce the oxygen storage capacity of the lunar miner and require another vehicle to make trips to and from the lunar miner to transport liquid oxygen from the miner to a stationary central storage facility. This procedure will require that extra energy be spent on transporting liquid oxygen since the vehicle will be empty for half of its round trip to and from the lunar miner. A second alternative is to attach a pipeline system from the lunar miner to a stationary liquid oxygen storage facility. This arrangement may be feasible considering the slow pace of the miner (0.6 meters per hour or about 142 meters per 336 hour work period).

APPENDIX A; CALCULATIONS

MOBILE LUNAR MINER SPEED

Variables:

u = fraction of soil that will be carried by the conveyor to process

x = fraction of oxygen extracted from lunar fines

O = required oxygen production rate

ro = density of lunar soil

V = volumetric flow rate of excavated lunar soil

v = velocity of miner

z = digging depth

w = digging width

Equations:

$$V = O/(ro*x*u)$$

$$v = V/(z*w)$$

Estmated values:

u = 0.5

x = 0.42

O = 228kg/hr

ro = 1800Kg/m

z =.5m

w =2m

V =(228 kg/hr)/((1800 kg/m3)(0.5)(0.42)) = 0.6 m3/hr

v =(.6 m3/hr)/((0.5m)(2m)) = 0.6 m/hr

AUGER GEOMETRIC CALCULATIONS

D = diameter of auger

W = width of auger

P = particle release velocity

R = angular velocity of auger

Sc = number of blades on auger

V = volumetric flow rate of excavated lunar soil

Vp = volume required per blade

Ba = cross sectional area of each scoop

Rev = revolutions

PI = 3.1416

B = blades

Equations:

$$Vp = \frac{V}{Sc/rev)*((R/2*PI)*Rev/Sec)*(3600\ Sec/hr)}$$

$$Ba = Vp/W$$

Estimated Values:

D = 1m

W = 2m

P = 0.75 m/s

Sc = 18

Vp= (0.6 m3/hr)/((18 B/rev)*(1.5rad/Sec)/(2*PI rad/rev))

*3600 sec/hr

Vp = 39 cm3/blade

Ba = (39*10**-5) m3/Blade / 2m = .195 cm2/blade

Calculation For Beneficiation Conveyor Speed

Variables:

ro = density of lunar fines

M = required mass flow rate of lunar fines

W = width of beneficiation conveyor

t = thickness of fines on conveyor

v = velocity of conveyor

Assumptions:

1. Required thickness of lunar fines on the conveyor will be approximately the average diameter of fine particles. This average diameter is about 120 micrometers or 120*10**-6

2. The average density of the layer of particle fines on the belt will be 1.8*10**3 kg/m3 (The average lunar soil density)

Equations: v = M/(ro*W*t)

Estimated values:

ro = 1.8*10**3 kg/m3

M = 543 kg/hr

W = 2m

t = 120*10**-6 m

v = 543/(1800*2*(120*10**-6)) = 1257 m/hr = .35 m/s

APPENDIX B
Figures, Graphs and Tables

Figure 1

4 BAR LINKAGE MOTION

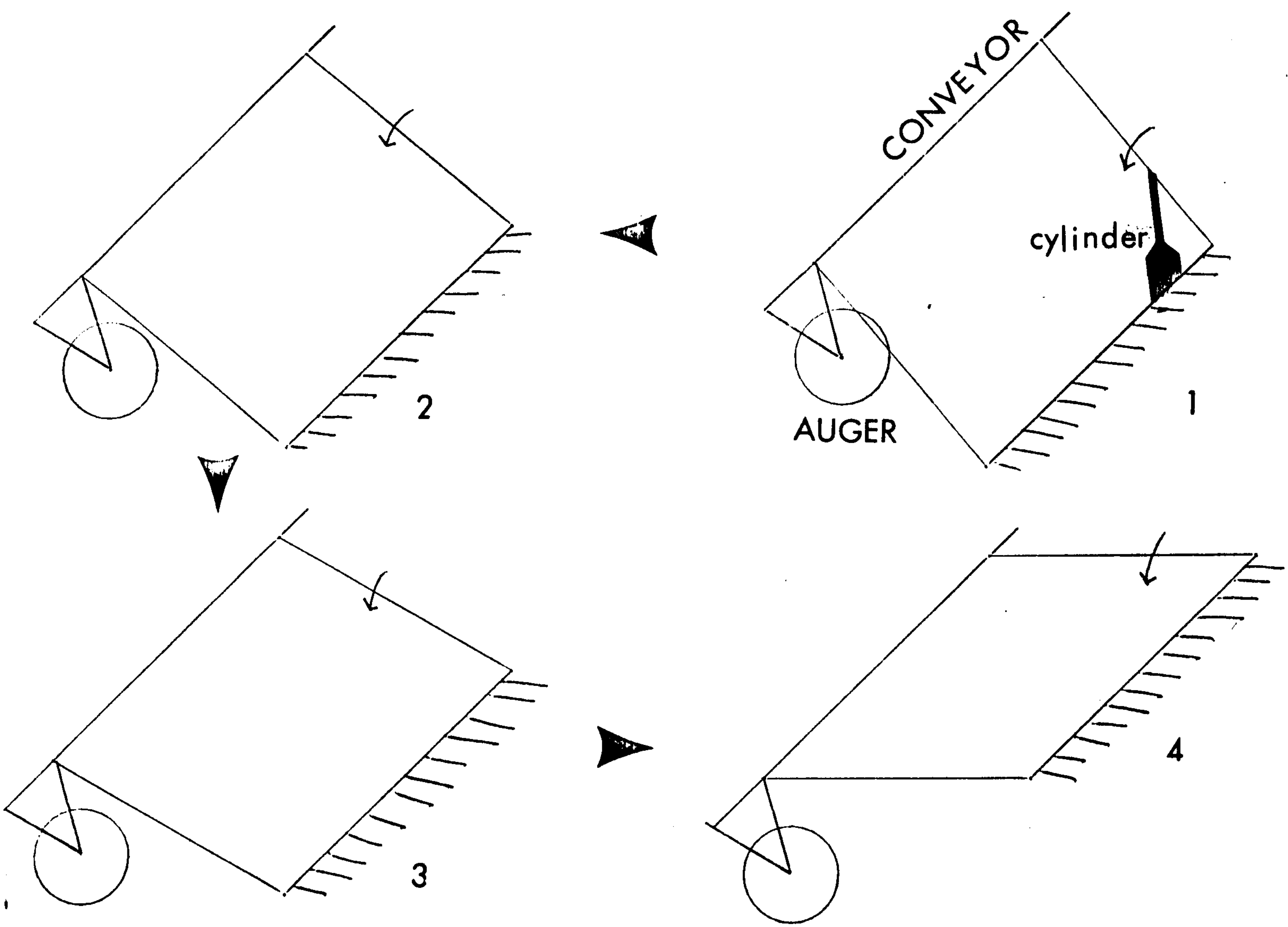


Figure 2

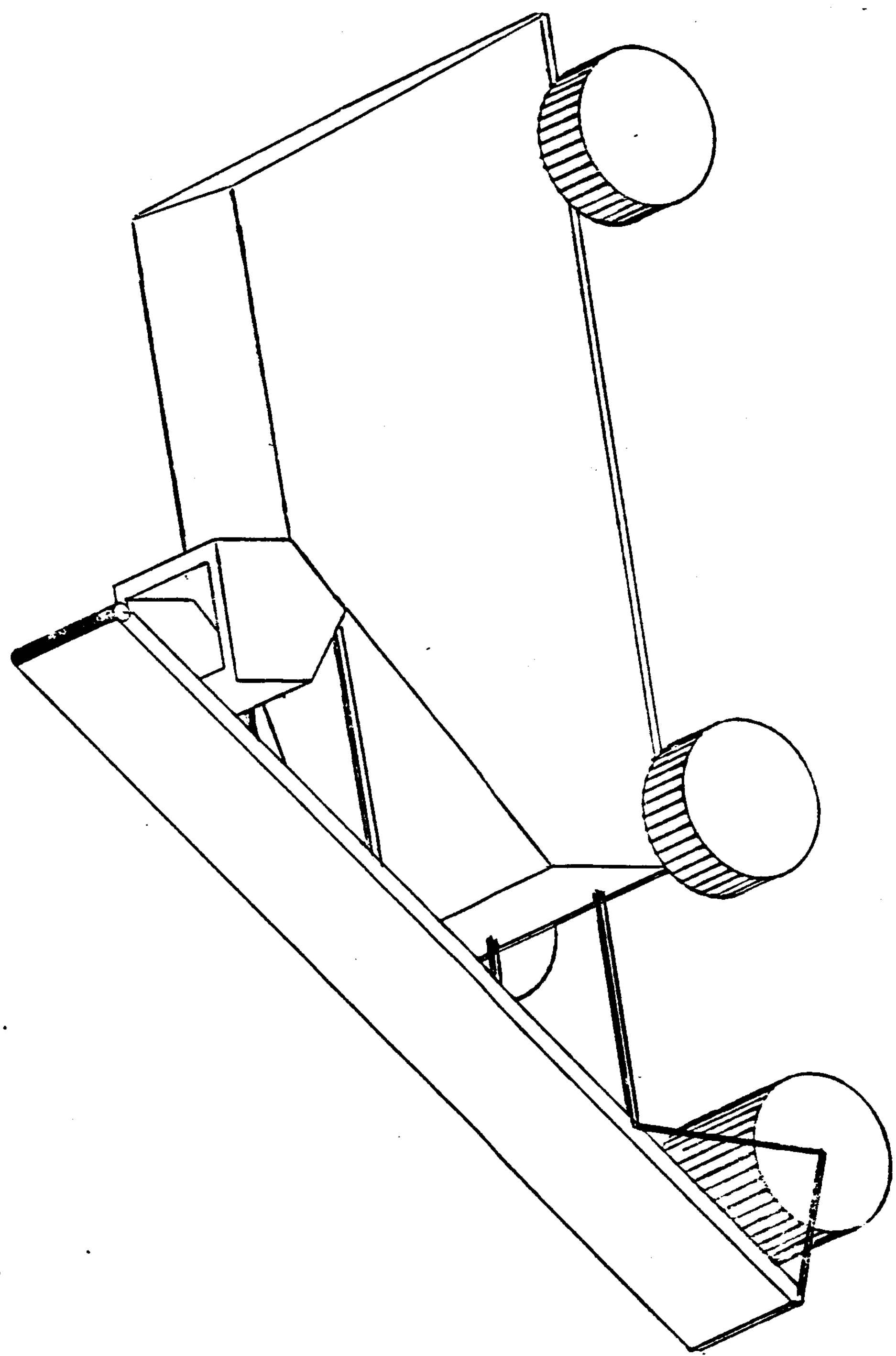
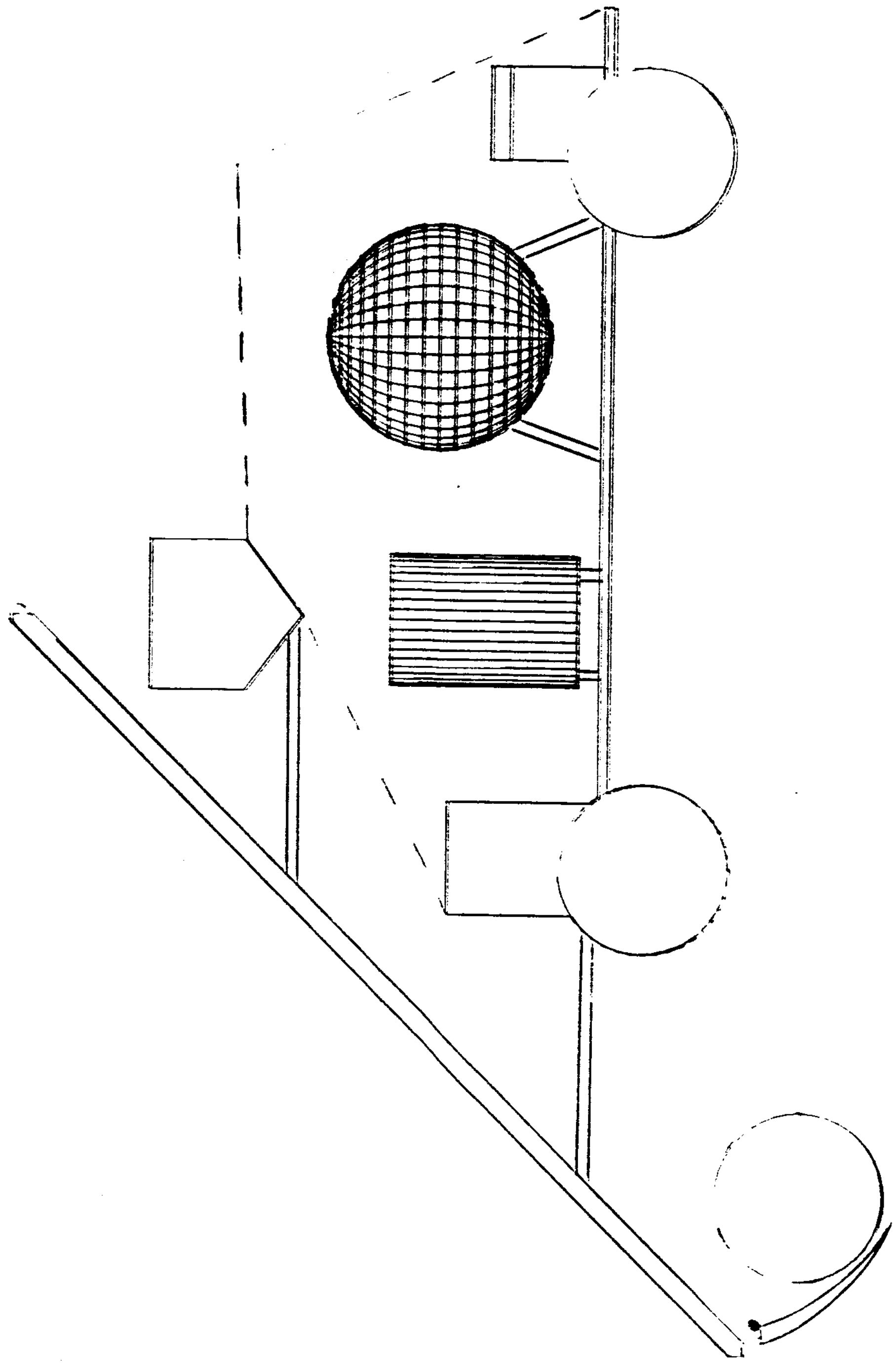


Figure 3



SIDE VIEW

Figure 4

LUNAR MINING AND OXYGEN EXTRACTION PROCESSES

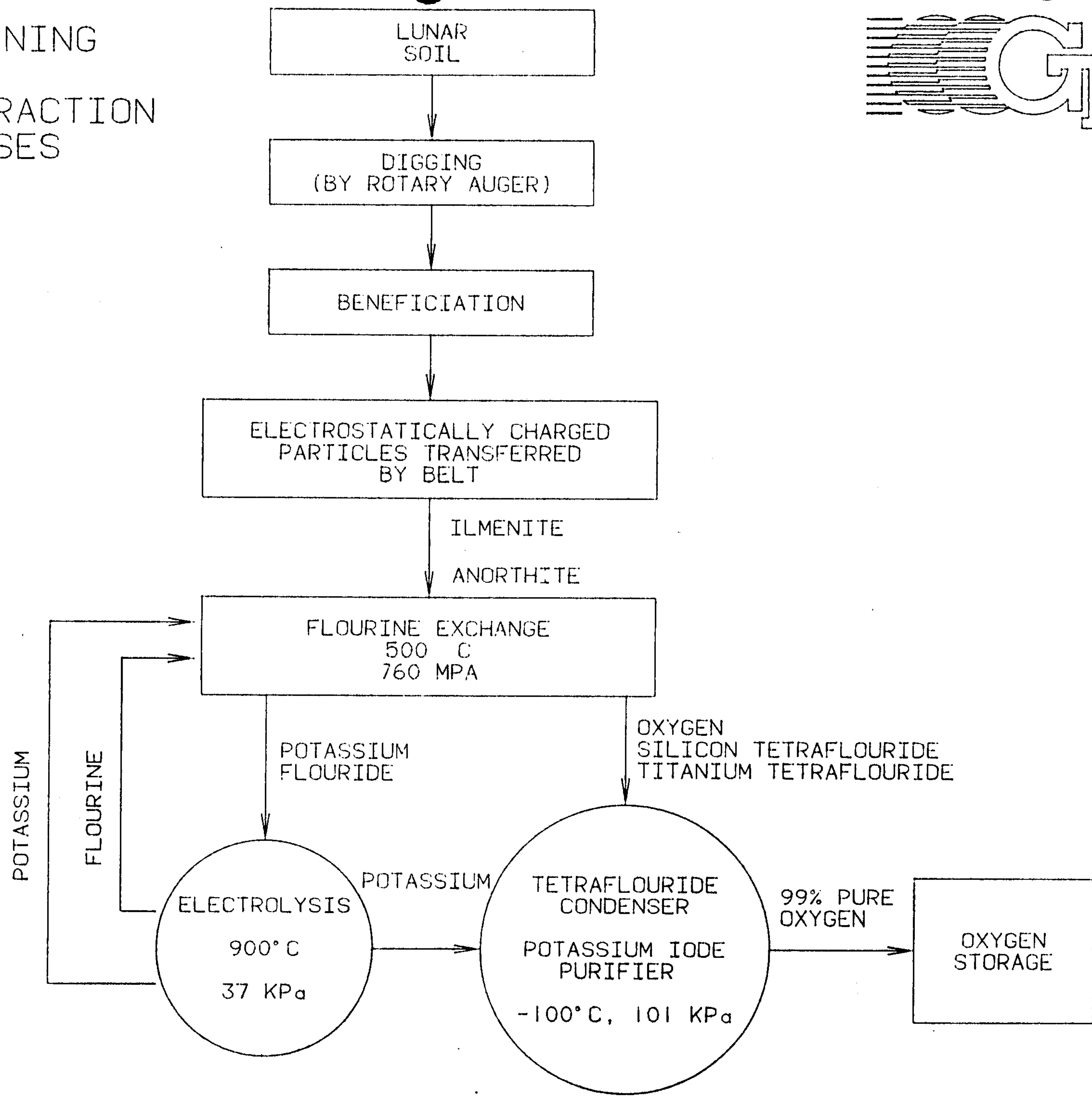
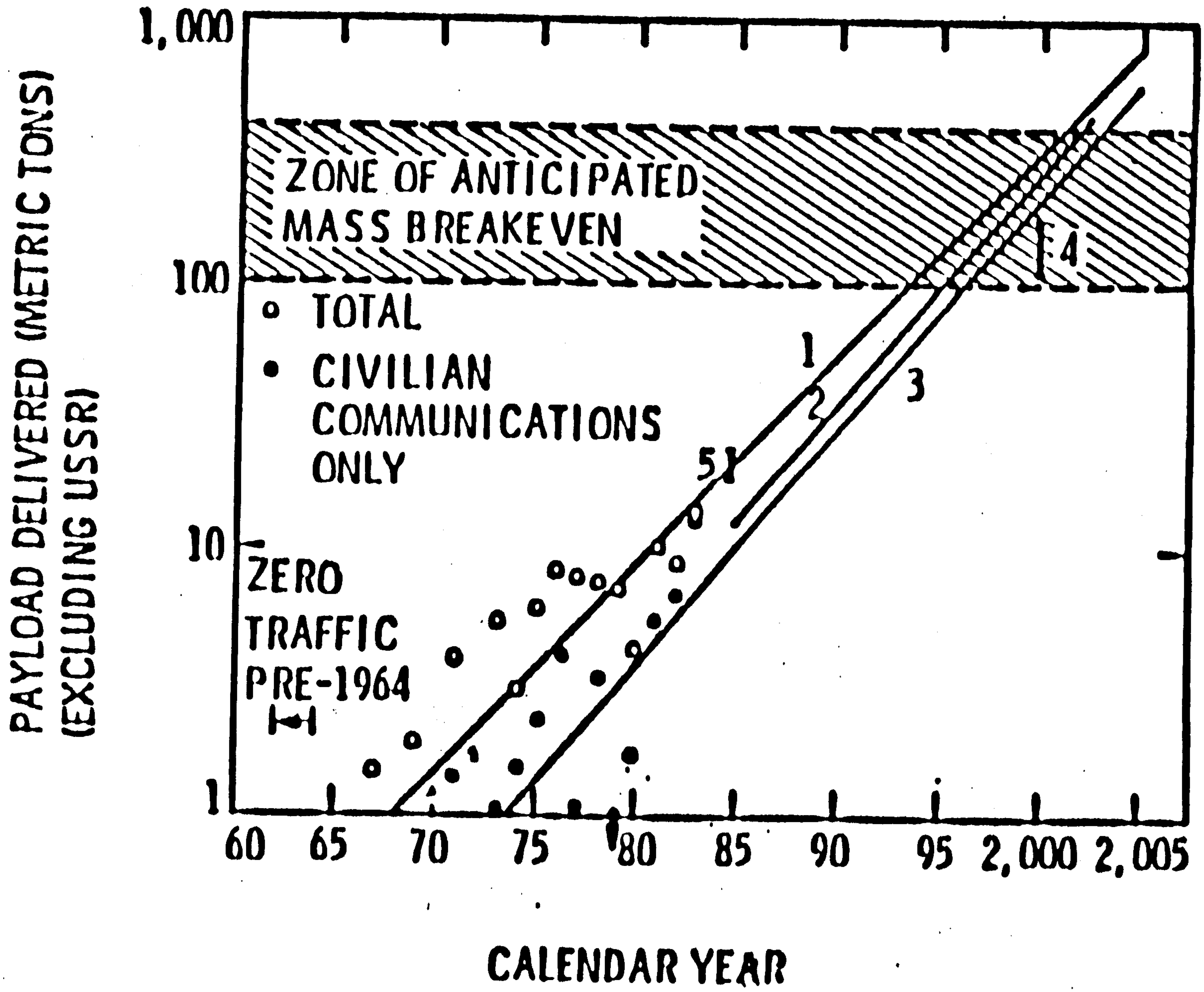


Figure 5

ANNUAL TRAFFIC TO GEOSTATIONARY ORBIT



[14]

Table 2

TABLE II. - COST AND SCHEDULE OF LUNAR-SURFACE OXYGEN PLANT COMPONENTS

Component	Hydrogen plant			Fluorine plant		
	Quantity	Total cost, millions of dollars	Schedule, months	Quantity	Total cost, millions of dollars	Schedule, months
LSM	2	80	36	2	80	36
Conveyor belts	2	10	18	2	10	18
Terminal funnel	1	2	12	1	2	12
Processing sphere	3	10	24			
Processing cylinder				2	15	48
Condenser	1	1	6	1	1	6
Electrolysis unit	1	40	48	1	50	60
Liquefier	1	40	48	1	40	48
Magnetic separator	1	3	36			
Electrical power[a]						
Solar array	1	250	30			
Nuclear				1	400	60
Structure	1	20	24	1	20	24
O_2 and H_2 storage tanks	20	40	18	20	40	18
Thermal shades	20	10	12	20	10	12
Liquid transfer	2	60	48	2	60	48
Radiator	1	3	18	1	3	18
		569			731	

[a]The two plants could use the same type of electrical power source.

Figure

METHOD FOR OBTAINING OXYGEN FROM LUNAR OR SIMILAR SOIL

Filed Feb. 28, 1972

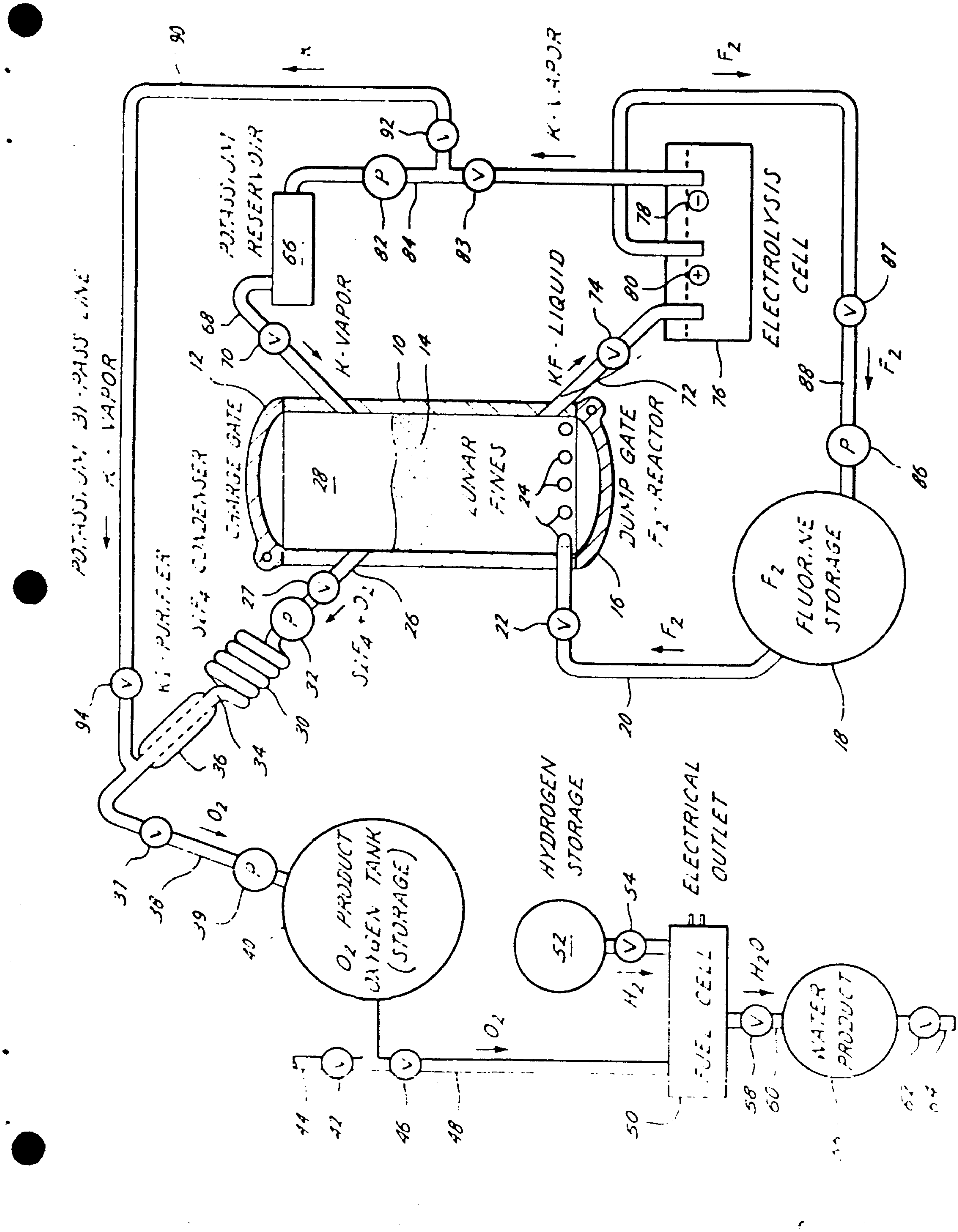
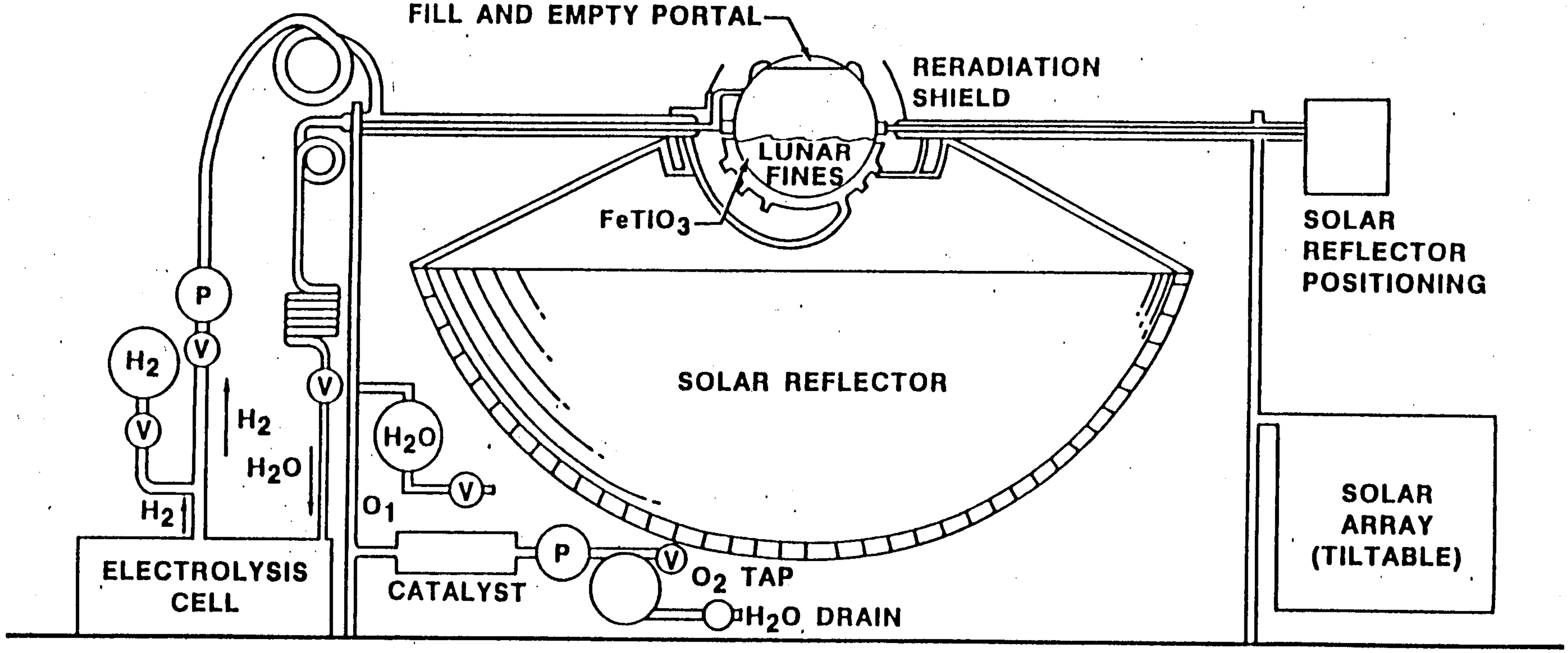


Figure 10

LSR LUNAR SURFACE RETURN — 84-00666 NASA

HYDROGEN REDUCTION SCHEMATIC

Lyndon B. Johnson Space Center



APPENDIX E

Alternate Designs

HYDROGEN REDUCTION

Hydrogen reduction is a process that takes concentrated lunar fines, ilmenite ($FeTiO_3$), and pumps in hydrogen gas at temperatures near 1500°C (see appendix D, figure 7). The by-products of this reaction are water, iron oxide and titanium oxide. The basic chemical equations for the production of water from ilmenite is;

$$FeTiO_3 + H_2 \longrightarrow Fe + Ti + H_2O$$

The water produced in hydrogen reduction, which is 88.8% oxygen by mass, will be sent through electrolysis to produce a 99.98% pure oxygen gas. Using a ceramic electrolyte there will be a build up of oxygen at the anode and hydrogen at the cathode. The resistance of the nominal 30% KOH electrolyte drops by a factor of 3 with a rise in temperature from 27° C to 92° C. The following are the nodal reactions taking place during electrolysis.

$$H_2O + 2e \longrightarrow H_2 + O^{*2-}$$

$$O^{*2-} \longrightarrow O^{*}_2/2 + 2e^-$$

The benifits of hydrogen reduction are that it's chemically and operationally simple, and it has a minimum earth lift requirement. The main disadvantage is that has very poor efficiency, in the level of 3.2%. It is also restricted to working with ilmenites, which causes 90% of the gathered material to be discarded.

The hydrogen will be recovered to be pumped back to the reduction process, while the oxygen is liquified for storage. The cost for production equipment and the necessary process sizes refer to appendix B table 4..

15. Williams, P.J., McKay, D.S., Giles, D.,and Bunch, T.E., _Mining and Benification of Lunar Ores_., NASA, 1979.